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### DEMAND FOR LARGE FREIGHTER AIRCRAFT AS PROJECTED BY THE NASA CARGO/LOGISTICS AIRLIFT SYSTEMS STUDIES

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NASA CARGO/LOGISTICS AIRLIFT SYSTEMS STUDIES

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SUMMARY

This paper examines the market conditions up through the year 2008 to provide a preliminary assessment of the potential for and the characteristics of an advanced, all-cargo transport aircraft. Any new freighter must compete with current wide-body aircraft and their derivatives. Aircraft larger than the wide-bodies may incur economic penalties and operational problems. A lower direct operating cost is not a sufficient criterion to base a decision for the initiation of a new aircraft development or to select aircraft characteristics. Other factors of equal importance that are reviewed in this paper include considerations of the system infrastructure, the economics of the airlines, and the aircraft manufacturer return on investment. The results of the market forecast and a computer simulation show that an advanced long range aircraft with a payload between 68 to 181 tonnes (75 to 200 tons) could generate a solid foothold beginning around 1994.

INTRODUCTION

Air cargo has been forecast to continue its growth rate through the turn of the century. The rate of this growth could be impacted by a number of factors only indirectly related to market demand such as terminal congestion, noise constraints, lack of appropriate aircraft, and regulatory impediments. The growth rate will in turn impact the way that the air cargo system evolves, and will largely determine the type of service that is offered. If the increase in airfreight ton-miles simply follows the expansion of overall cargo transportation, with the air mode maintaining its current share of around 0.1 percent, then the future market will experience no substantive changes from today's emphasis on small shipments and high value high-priority express service. On the other hand, revolutionary changes in air cargo operations could bring a significant penetration of the traditional surface mode traffic. To achieve this objective, the air cargo transportation system must offer major cost reductions and a new concept in service to the shipper in order to induce regular, high volume traffic.

Only if the second alternative eventuates will there likely be a demand for a new, advanced technology freighter before the year 2000. To evaluate the potential for the advanced cargo transport, NASA let two separate contracts for a study entitled "Cargo/Logistics Airlift Systems Study (CLASS)." The objectives of this study include: (1) the evaluation of the present air cargo operation, (2) the estimation of the level and characteristics of future air cargo demand, (3) the postulation of the role of an advanced freighter in stimulating future demand, and (4) the determination of the most appropriate aircraft to serve the 1990-2000 air cargo market. The first three objectives have been accomplished and the results are reported in references 1-3. The purposes of this paper are (a) to briefly summarize those results from references 1 and 2 that impact the potential for the integration of large, advanced freighters into the future air cargo transportation system and (b) to report on the fourth objective enumerated above to determine the most likely aircraft that could meet the projected demand at the turn of the century.

#### SYMBOLS

ALR	advanced long range aircraft, range = 7022 km (4364 statute miles)
ASR	advanced short range aircraft, range = 3218 km (2000 statute miles)
CLN	current large narrow body aircraft (DC-8, B707)
CSN	current small, narrow body aircraft (DC-9, B737)
CW	current wide-body aircraft (DC-10, B747)
DLR	derivative long range aircraft, range = 7022 km (4364 statute miles)
DMR	derivative medium range aircraft, range = 5151 km (3200 statute miles)
DSR	derivative short range aircraft, range = 3218 km (2000 statute miles)
EUACF	equivalent uniform annual cash flow
OAG	Official Airline Guide
ROI	Return on Investment
TKM	tonne - kilometers
TSM	short ton - statute miles
L/D	percent change in the cruise lift-to-drag ratio
SFC	percent change in specific fuel consumption

WENG	percent change in the weight of engines
WFURN	percent change in the weight of power systems, elective lighting systems, furnishing, and air conditioning
Wp+N	percent change in the weight of pylon and nacelle
WSTRU	percent change in the weight of aircraft structure excluding pylons and nacelles

### AIR CARGO SYSTEM - CURRENT AND FUTURE

The future of the air cargo transportation system will undoubtedly be affected by national and international issues, but the nature of that influence is difficult to predict. The establishment and maintenance of a stable and favorable economic and regulatory climate between major industrial powers is a necessary but, of course, not sufficient condition for the sustained growth of air cargo. A highly favorable environment is also required for any substantial system improvements to be implemented. The first portion of this paper examines some of the broader system concerns followed by an analysis of the air cargo infrastructure and airport operations, and concludes with an analysis of the economic viability of a new freighter in competition with current and optimal derivative aircraft.

The multiplicity of influences that will impact the future of the air-freight industry is illustrated in Figure 1. This hierarchy of decision criteria is by no means complete, but is offered to suggest the complex issues that influence the nature and extent of future operations. The decision criteria are listed in a sequence of levels such that each succeeding level encompasses a broader spectrum of constituent interest. Generally, the higher the level, the further removed is the decision process from the market determinants that govern mode choice on a supply and demand basis. Decision impacts at a given level are passed to lower levels as a rule, with changes at the lower level rarely effecting the major constituent interests above. This type of presentation suggests that there are more than market forces at work in determining the character of airfreight and hence the viability of advanced freighter aircraft.

The two CLASS contractors (refs. 1,2) identified and analyzed a number of issues and criteria representing all of the levels identified in Figure 1. Two separate contracts were awarded for the CLASS project because the proposals offered by the Lockheed and Douglas teams were comprehensive yet differed significantly in the study approach. An outline of the two methodologies is given in Figure 2. Lockheed's approach centered around the Case Studies task (shown in heavy outline) in which the survey respondents were first exposed to the 1990 Scenario. This scenario was developed in consultation with the Department of Transportation and NASA and included a general description of the world economic condition and a projection of the cost and performance characteristics of all freight transportation modes and supporting infrastructure in the year 1990. The Demand Forecast, the next task in the block diagram

of Figure 2, was then derived by combining the results from the Case Studies with macro freight transportation statistics. The Analysis of Advanced Systems task developed an optimal air transportation system around the demand derived from earlier phases of the study. The Current Operation Analysis simply documents current airfreight operations and provides a contrast to the advanced system. In this approach, then, the emphasis was on a user response to a new, more efficient and cost-effective air cargo service.

In contrast, a heavy emphasis in the Douglas approach was on the Current Operations Analysis which involved extensive field surveys at terminals and airports followed by a thorough analysis and interpretation of the air system as it functions in mid-1978. Results of the Current Operations Analysis were used to formulate the Case Studies and provide the starting point for the 1990 Scenerio. The results from the Case Studies also contributed to the Demand Forecast which in turn impacted the 1990 Scenario development. The Analysis of the Advanced System and the projected system attributes were developed iteratively with the 1990 Scenario. Douglas thus traced the potential evolutionary development that could lead to an advanced air cargo system, with attributes not postulated before the performance of the Case Studies but determined by the execution of the study. The final block in dashed lines on Figure 2, Requirement for New Freighter, represents work still in progress by the Douglas company and the preliminary findings from that task will be highlighted later in this paper.

### Airport Operations

In-depth surveys were conducted at five domestic airports and sixteen terminals. Each site was examined for operational efficiencies, landside access, saturation, growth potential, and constraints on operations or growth due to institutional restrictions such as curfews. Most major U. S. airports have ground access problems which restrict cargo influx and efflux thereby reducing the speed advantage offered by the air mode. Expansion of cargo facilities and repair of existing capabilities has been hampered, and sometimes terminated by environmentalists and no-growth interest groups. Many terminals were found to have inadequate staging, make-up and storage facilities, and expansion at many of the existing sites is precluded.

Runway, gate and terminal congestion represents both an impediment to air cargo growth and a serious financial loss to the carriers. Runway delays at Chicago O'Hare alone cost carriers \$44 million in 1975 and wasted 67 million gallons of fuel. Adding to the congestion at several major airports is the use of these cities as transfer hubs in the carriers' distribution systems. The hub-spoke service allows the airlines to consolidate both passenger and cargo demand between many cities and to use significantly larger aircraft between the hub airports. However, airport congestion has forced the diffusion and increase in the number of these transfer hubs rather than the more efficient consolidation of transfer operations at a few superhubs. This proliferation of transfer traffic will reduce the need for a superlarge aircraft to serve the "wholesale" delivery role between such superhubs.

Analyses of the airport surveys indicate that there is little chance of new airport construction during the 1980's. Cargo terminal expansions are planned for Atlanta, Chicago O'Hare, and Los Angeles International, but increased congestion and regulatory constraints will serve to constrict air cargo operations and impact the design of advanced aircraft which could be used at these and other major domestic hubs. Noise regulations imposed by localities will dictate stringent design conditions for new aircraft. Current airports already force limitations on aircraft size and weight. Runway, taxiway, and apron area dimensions and load-bearing capacities are such that these criteria will prohibit or severely limit the operations of aircraft larger than the B747. Other aircraft design aspects currently dictated by existing regulations include wing span limits, landing gear footprints and fuselage length. There are many airports where the wide-body aircraft cannot park at the terminal unless the adjacent gate positions are empty or contain a small aircraft. Two 747's cannot pass each other on inbound and outbound taxiways at the world's busiest airport, Chicago O'Hare. The current ultimate constraint on wing span is the separation standard used in airport design. FAA standards specify 67 meters (240 feet) as the maximum span for future Group 4 airports. Again by FAA standard, the maximum allowable tread width is 15.2 meters (50 feet). Although no FAA ruling is made for aircraft length, almost every terminal gate position has a maximum allowable fuselage length so the aircraft will not violate the clear area for other aircraft. For those airports having close parallel runways, the aircraft must not be so long that it cannot cross one active runway and wait for clearance to cross the second active runway. Possible solutions to these problems may rest in novel aircraft concepts such as air cushion landing gear or in the development of all-cargo airports. If a solution is not forthcoming, airport limitations will impact future aircraft design and will clearly preclude the possibility of operating aircraft larger than today's wide-bodies.

### Hub-Spoke Distribution System

The preceding findings thus suggest that current airport congestion, incompatibilities with the terminal facilities, airport layouts, and the existing route network and supporting infrastructure preclude the utilization of aircraft exceeding the size of the B747. Any such large freighters would be used primarily for intercontinental airfreight operations and the most likely systems design would employ a relatively small number of world-wide hub centers. A practical network may be operational and economically feasible with as few as ten worldwide hub terminals (ref. 4). In this hub and spoke concept, the cargo is delivered to the hub by surface mode or by a short-haul airplane. The economics and possible operation of the hub-spoke system are examined in references 5 and 6. The cargo hubs could operate far more efficiently if they are situated away from the passenger transfer hubs, but this would lead to difficulties in the transfer of belly-pit cargo.

The cargo hub concept will soon be tested in the Northeastern United States when a new 3.7 km (12,000 feet) runway is opened at Stewart Airport (ref. 7). Formerly Stewart Air Force Base, this facility has been turned over to civil authorities who have promoted the location as an ideal cargo hub.

The airport is located 60 miles north of New York City at the intersection of two interstate highways and about four miles from a deepwater maritime facility at Newburgh, New York. Stewart is within 10 trucking hours of half the U. S. population and can easily serve the cargo traffic currently passing through an over-crowded Kennedy Airport. With its 1552 acres of runways and terminals, and adequate space for expansion, Stewart claims to be second in size only to Dallas/Fort Worth among U. S. airports. As a stimulus to foreign trade, Stewart boasts the only operational foreign-trade zone located on an airport. The developers of this cargo facility have met all of the criteria for the hub concept. It remains to be seen how this intermodal cargo center will impact air cargo traffic and distribution patterns in the northeast corridor.

International institutional constraints could represent the largest barrier to the development of hub-spoke operations and the large, dedicated hub-to-hub aircraft. Bilateral and multilateral agreements between nations often place restrictions on such operational factors as routes to be flown by the respective nations' aircraft, frequency of flights over a given stage, gauge changes enroute, and the freedoms granted to the carrier in dispatching cargo for other nations. The issue of trade agreements as shown in figure 1 has an impact on cargo operations that is far removed from shipper mode choice, yet these global, socio-political decisions could easily impact the selection of a new freighter design.

#### Containerization

The type of containers that evolve to serve the growing air cargo market will impact the design of new freighter aircraft. Most of the shippers who took part in the Case Studies were critical of current air containers because of their size and shape. Many expressed the opinion, for example, that the use of Igloo containers would inhibit a distribution system already built around the rectangular-shaped surface containers. The shippers were clear in their desire for an air operation which offers intermodal container capability. The airport and terminal surveys showed that only with the advent of large and more standardized containers will a higher degree of mechanization be achieved. Air cargo terminals are currently highly labor-intensive which is the predominant reason for the significantly higher terminal operating costs for the air mode compared to truck operations. The adaptation of the intermodal container thus offers advantages to many parties in the air cargo operation. Maximum operational efficiency for the carrier is achieved when the shipper owns, maintains, loads, and delivers his own standard container to the carrier terminal.

#### Summary of CLASS Results on System Improvements

Both CLASS contractors examined the potential system improvements that might evolve in air cargo operations and Douglas quantified the resulting impact on operating costs and airfreight rates. The results are shown in figure 3. The six items broken into two time frames represent a reasonable consensus from the two contractor teams for improvements that can lead to an

advanced air cargo system. The actual savings that can be achieved will be dependent on how the system evolves; the cost figures on the right side of figure 3 reflect the potential benefits for the system developed in the CLASS scenario. Improvement to the current infrastructure can occur from 1978 to 1985 with off-the-shelf technology, which when combined with higher load factors for aircraft and containers, can provide up to a 16 percent reduction in Total Operating Costs (TOC) and a 15 percent rate reduction. These benefits are derived primarily from a reduction in IOC (Indirect Operating Costs). Beyond 1985, with IOC reductions accomplished, there will be a greater emphasis on DOC (Direct Operating Cost) reduction. Because advanced freighter concepts will only represent part of the freighter fleet, the total system benefit from reductions in DOC will not be large, with only a 3 to 6 percent reduction in rates directly traced to the advanced aircraft. However, the economy of scale and aircraft/airport compatibility benefits from reduced IOC are partly attributed to the introduction of advanced freighters which have full intermodal capability and are designed to facilitate the cargo loading process. Before accumulating the rate reductions on Figure 3, a 4 percent rate increase was considered needed to stabilize the earnings of the cargo carriers. The final net rate reduction from 21 to 24 percent is postulated. Thus, the trend to the mid-1980's could be toward modest rate reduction, increased carrier profits, and proliferation of incentive tariffs directed toward increasing customer-loaded containers, terminal productivity, and container volumetric utilization. The introduction of an advanced freighter will probably occur only in the latter stages of the second period, 1985-2000.

#### FUTURE MARKET REQUIREMENTS FOR FREIGHTER AIRCRAFT

The previous sections of this paper have reported on those aspects of the NASA Cargo/Logistics Airlift Systems Study (CLASS) that impact the potential development of large freighter aircraft. Referring back to figure 2, the discussion to this point has centered on the Current Operations Analysis and the results of user Case Studies. The results have shown that the air cargo system is unfavorably disposed toward the introduction of aircraft larger than current wide-bodies unless a new, dedicated hub/spoke network evolves. The remainder of the paper will report on the preliminary findings from a computer simulation of the air cargo market from 1978 to 2008. Several advanced cargo aircraft are competed against current and derivative freighters.

#### Forecasts

The first step in analyzing the potential timing for new freighter development is the derivation of a traffic forecast. The system analysis reported herein was conducted by Douglas and hence is based upon their cargo market forecast developed in the CLASS project (ref. 2). The forecast was based on a sound background of current and past operations, including regional traffic flows (city-pair and country-pair) for the U. S. domestic, U. S. international, and 44 foreign carrier markets. Next, a series of econometric behavioral equations were developed for each market segment considering the

GNP growth, inflation, and currency rate variation as affected by historical and forecast trends for the U. S. and 31 major foreign countries. The baseline Scenario for the U. S. domestic market was based on a constant value of the price ratio of air to motor freight. For the U. S. international and foreign carrier markets the baseline forecast was based on the 1976 airfreight yield held constant over the considered period.

Since the study objective was to investigate aircraft that could become operational in the post-1990 time period, a time period out to the year 2008 was considered. In developing the extended forecast, the baseline growth discussed above was modified to account for system-induced growth factors developed in the course of their CLASS study. In addition, the magnitude of the mail and express components of the cargo market were evaluated and included in the market forecast.

The magnitude of the tariff reductions shown in Figure 3 that are expected from future system developments are used to determine the nature of cost and service elasticities. Using these data, market growth factors were defined for each of the following system changes postulated to occur prior to 1990:

- 90 percent shipper-loaded containers
- Economies of scale
- Improved cargo terminal equipment and procedures
- Improved aircraft-airport compatibility
- Reduced import storage time
- Increasing airline profit
- Advances in aircraft technology and sizing
- Increased number of cities served
- Increased aircraft load factor

With the exception of the impact of increased airline profit, the resulting market growth factors are all positive ranging from a plus 1.3 percent due to aircraft-airport compatibility to 11 percent for achieving 90 percent shipper loaded containers.

One of the more important factors affecting the sizing of future air freighter is the expected market share to be carried in these all cargo aircraft. In the Douglas forecast this share was increased from the current values of 40, 65, and 40 percent for the U. S. domestic, U. S. international, and foreign markets respectively to the following values by the year noted:

#### All-Cargo Aircraft

	Market Share - Percent			
	1978	1980	1990	2000
U. S. Domestic	40	45	50	55
U. S. Int'l	65	70	70	70
Foreign	40	45	50	60

For the three markets combined, the weighted all-cargo aircraft share was increased from the 44 percent in 1978 to 60 percent by the year 2000. This 16 percent increase was considered a viable change over the 22 year period.

The cargo market forecast for all-cargo aircraft shown in figure 4 is developed by combining, over applicable years, the preceding induced growth factors with the annual growth of the baseline forecasts. The all-cargo market share is then derived based upon the resulting revenue tonne-kilometers (revenue ton-miles). Finally the mail increments are added and a new annual change schedule computed. The resulting average annual growth rates for the period 1978 to 2008 are 8.6 percent for U. S. domestic, 7.9 percent for U. S. international, and 12 percent for the foreign market.

In addition to the market demand the aircraft design characteristics will be affected by system variables that are dependent upon changes in the total environment and upon the accompanying market forces. Among these variables are the distribution of cargo movement, inflation, fuel cost, indirect operating cost, and tariffs. Such factors can exert a strong influence upon system economics and hence upon the requirements for the aircraft making up that system. Therefore, values for these factors are forecast for the considered time period and then entered into the Douglas fleet simulation model as independent variables (see Fig. 5).

Analysis of past and future forecast trends indicate a very small potential change in the relative distribution of cargo movement with range and hence this factor was not considered in developing the model. An average annual inflation rate of 6 percent was applied to all operations from the base year of 1978 out to 2008. However, the price of fuel is increased an additional 3 percent per year beyond 1985 based upon the forecast problems of supply and demand. The resulting starting prices for fuel for each of the considered time periods (with price inflated from the base year) were 11 cents per liter (43 cents per U. S. gallon), 19 cents per liter (71 cents per U. S. gallon) and 48 cents per liter (181 cents per U. S. gallon) for 1978, 1984, and 1994 respectively.

### Advances in Technology

Considerable effort is currently being devoted to research and development related to improving aircraft efficiencies. These "energy efficient" programs being sponsored and/or performed by the NASA and industry will certainly result in technology advances applicable to interim derivatives and future dedicated cargo aircraft. The 1980 technology encompasses five developments that were considered viable for the derivative aircraft projected to become operational in 1985. Similarly, the 1990 technology encompasses eight developments considered applicable to new dedicated cargo aircraft projected to become operational in 1995. Utilizing available study and test results, Douglas and NASA first identified the incremental changes to aircraft parameters that could result from each of the considered developments. The resulting incremental changes presented in Tables 1 and 2 are based upon the respective values for contemporary aircraft.

The 1980 developments were viewed as an interim step toward achieving the 1990 technological objective. It was also assumed that the 1985 generation aircraft would develop as derivatives of contemporary configurations. Selection of the 1980 items therefore considered not only the anticipated state of development but also the limitations imposed by the derivative approach to aircraft development. As an example, the 1980 technology applications included composites applied only to secondary structural elements within the pylons, nacelles, vertical tail and fuselage. The 1990 level considered application to both secondary and primary structure varying in scope from 8.5 percent, by weight, of the wing to 74 percent of the nacelle and pylon. In a like manner it was postulated that while the 1995 design would achieve an improved lift-to-drag (L/D) ratio through use of the supercritical airfoil, the 1985 design would utilize a combination of winglets and active lateral control to achieve about half the 1995 increase in L/D and with negligible structural weight penalty.

Considering the current state of development, the application of active flight controls was limited to only the lateral axis for the 1980 time period. However, by 1990 the application was expanded to include longitudinal control as well, thus providing for a more aft center of gravity and reduced horizontal tail area. Similarly, adhesive bonding and improvements in aircraft systems would be premature for 1980 application, but would be available for 1990 implementation.

### The Aircraft Selection Process

With the forecasts of the cargo markets, and the definition of the system variables and technological developments completed, the Douglas effort proceeded to the definition of requirements for future cargo aircraft, utilizing their system simulation program called FRAME (Future Requirements and Advanced Market Evaluation). This program was exercised to parametrically identify future aircraft requirements in terms of payload, range, speed, operating cost, acquisition cost, return on investment, and the equivalent uniform annual cash flow (EUACF) for the time period and the aircraft characteristics considered. The network used is defined by the all-cargo portion of the August 1978 issue of the Official Airline Guide (OAG). Analysis is performed for the total network and the combined U. S. domestic, U. S. international, and foreign cargo markets. Characteristics for the parameteric aircraft are developed with the aid of the Design and Cost Subroutine based upon current aircraft characteristics and utilizing the incremental changes due to advanced technology shown in Tables 1 and 2. Considering the projected introductions of the derivative aircraft in 1985 and the advanced dedicated aircraft in 1995, analysis is performed over the time periods 1978-1985, 1984 to 1995, and 1994 to 2008. The one year overlaps are employed to assure continuity.

## Current Aircraft

The projected fleet mix assuming only the availability of current aircraft over the first of those time periods is shown in figure 6. In order to reduce the quantity of data that had to be handled, the current aircraft types identified in the OAG were segregated into three groups, CSN, CLN, CW, each representing one of the three general classes of current all-cargo aircraft namely: small narrow body (i.e. DC-9 and B737), the large narrow body (i.e. DC-8 and B707) and the wide-body (i.e. B747 and DC-10), respectively.

Due to the growing market the small aircraft (CSN) phased out by 1984 while the number of CLN class aircraft continue to increase out to the year 1982. The number of wide-bodies required (CW) continue to grow throughout the period reaching 95 units by 1984. The analysis that follows assumes that the current aircraft will begin competition with derivative aircraft in 1984. An extension of the analysis of figure 6 shows that if the current aircraft types were utilized out to 1998 almost 750 of the CW class aircraft would be required to meet the forecast market demand in that year.

## Derivative Aircraft

Derivative aircraft based upon the 1980 technology developments shown in Table 1 are introduced in 1985. Analysis was performed parametrically over the period 1984 to 1998 for a range of payloads from 90.7 tonnes (100 tons) to 453.6 tonnes (500 tons). Considering trends identified from the 1967, 1971, and 1978 OAG reports in combination with potential future world changes, two aircraft ranges were selected jointly by Douglas and NASA personnel. These ranges were 3218 kilometers (2000 statute miles) for the short range derivative (DSR) aircraft and 7022 kilometers (4364 statute miles) for the long range derivative (DLR) aircraft. Results of the derivative analysis are presented in Figures 7 and 8.

The data of Figure 7 defines the airlines' economic situation covering total fleet operations over the years 1984 to 1998. All dollar values are referred to 1984 dollars which are derived from a constant inflation factor of 6 percent per year from 1978. The ordinate of Figure 7, equivalent uniform annual cash flow, is defined as a cash flow value which if applied uniformly over each considered year would provide a total cash flow equivalent to that provided by the actual non-uniform annual cash flows. Also shown is the resulting airlines return on investment (ROI) based upon the total investment and the total cash flow experienced between 1984 and 1998.

The following five potential fleet operations are identified in Figure 7:

- o CLN, CW (REFERENCE) - current aircraft competing with one another
- o DSR, CLN, CW - the optimum short range derivative, 149.7 tonnes (165 ton) payload, competing with the CLN and CW aircraft.

- o DLR, CLN, CW - the optimum long range derivative, 149.7 tonnes (165 ton) payload, competing with the CLN and CW aircraft.
- o DMR, CLN, CW - the optimum medium range derivative, 149.7 tonnes (165 tons) payload, competing with the CLN and CW aircraft.
- o DSR, DLR, CLN, CW - the optimum short and long range derivatives competing with one another and with the CLN and CW aircraft.

The current aircraft fleet (REF) would be the least desirable while the combination fleet (DSR, DLR, CLN, CW) would be the most cost-effective course of action for the carrier. This combination fleet gives the highest ROI, nearly the lowest investment, and a greater cash flow than either the DSR or DLR when competing alone. However, due to the low number of units required (approximately 210 DSR and 180 DLR) both aircraft types would probably not be built. This concern is reinforced by the fact that the DMR fleet provided a cash flow equal to that of the combination with a slight reduction in ROI (less than 1 percent) and a relatively small increase in total investment (less than three percent). The DMR was therefore chosen as the more probable development. Requirements for this optional derivative aircraft are identified in the lower right portion of Figure 7. The 149.7 tonne (165 ton) payload for the DMR aircraft was chosen on the basis of optimizing the airline ROI, cash flow and total investment for the medium-range market.

The fleet mix resulting from the competition of the DMR, CLN and CW aircraft is shown in Figure 8. The market grows sufficiently up through 1986 to cause the CLN aircraft to be replaced by the larger CW; however, after 1986 the DMR begins to replace both these current aircraft types. The 1984 fleet that competes with the advanced aircraft in 1995 consists of approximately 250 DMR, 100 CW, and 10 CLN. In the absence of any advanced, all-new aircraft, the number of DMR units required increases to over 800 by the year 2008.

#### Advanced Dedicated Aircraft

Following the same procedures as in the analysis of the derivative aircraft, the advanced dedicated cargo aircraft was investigated parametrically over the range of payloads varying between 90.7 tonnes (100 tons) and 544.3 tonnes (600 tons) for each of the selected ranges. Fleet results for the advanced short range (ASR) (3218 km (2000 statute miles)) and the advanced long range aircraft (ALR) (7022 km (4364 statute miles)) are presented in Figure 9 for the following four fleet combinations:

- o DMR, CLN, CW (REFERENCE) - DMR, 149.7 tonnes (165 tons) competing with CLN and CW aircraft.
- o ASR, DMR, CLN, CW - three payload versions of the advanced short range aircraft competing with the

DMR, CLN, and CW aircraft.

- o ALR, DMR, CLN, CW - five payload versions of the advanced long range aircraft competing with the DMR, CLN, and CW aircraft.
- o ALR, ASD, DMR, CLN, CW - ASR, 272 tonnes (300 tons), and ALR, 453.6 tonnes (500 tons) competing with one another and with the DMR, CLN, and CW aircraft.

Both the short and long range versions of the advanced aircraft give considerable gains in ROI and decreases in investment relative to the reference fleet. (Note that there are different reference fleets in Figs. 7 and 9). These data show that the market demand for the 1994-2008 period will grow sufficiently to favor the long range aircraft which results in an ROI of 27 to 28 percent compared to a little over 21 percent for the reference fleet.

The airline economic data shown in Figure 9 indicates the 272 tonne (300 tons) ASR and the 454 tonne (500 ton) ALR to be the more desirable choices. When these two versions compete with each other and with the reference aircraft the resulting combination provided an increase in ROI and cash flow compared to the 454 tonne (500 tons) ALR. However these gains were not considered sufficient to substantiate the development of both the ALR and ASR aircraft; under these conditions, the ALR is clearly the better choice of the two designs.

An additional factor which Figure 9 does not consider is the manufacturers return on investment. While a larger aircraft may be more favorable to the airline, the smaller number of units required may preclude a profit to the manufacturer unless he substantially increases the cost per unit, thereby reducing the airline ROI. The data in Table 3 shows that a positive ROI for the manufacturer will occur for payload sizes less than about 181 tonnes (200 tons). These values were developed assuming one manufacturer and an aircraft price based upon 200 units. If there were two or more manufacturers, this problem would be further aggravated. Since the larger portion of required units will be utilized in the foreign market, (Fig. 4), the likelihood is high that more than one manufacturer will be involved.

The problem of manufacturer profit is accentuated in the case of the dedicated freighter compared to that of the derivative. For the latter there is the additional passenger market that can add considerably to the total number of units manufactured. On the other hand, the dedicated aircraft is solely dependent upon the growth of the air cargo system unless past practices are reversed and the industry begins to consider adapting a new dedicated cargo aircraft to passenger operations.

Investigations were conducted to determine the impact of providing the aircraft manufacturer with a reasonable ROI regardless of the number of dedicated aircraft required. Analyses identified the size of the ALR aircraft that would provide a maximum ROI for the airline while assuming a fixed 15 percent ROI to the manufacturer. Results are presented in Figure 10 along

with the previous data points based upon maximizing only the airline ROI. Assuring the manufacturer a fixed ROI completely reverses the relationship between payload weight and the airline economic parameters. In this case, the payload size that provides the highest ROI and lowest investment for the airline drops to 68 tonnes (75 tons) compared to the previous value of 453.6 tonnes (500 tons). The rapid deterioration at payloads less than 68 tonnes (75 tons) is due to the accompanying rapid increase in trip cost. As the payload is increased to 90.7 tonnes (100 tons) from the 68 tonnes (75 tons) the airline investment increases less than 3 percent, the cash flow increases about 1 percent while the change in ROI was essentially negligible. Increasing payload further to 181.4 tonnes (200 tons) results in an additional increase in investment of 8 percent with a 4 percent increase in cash flow and a small decrease in ROI, slightly over 1 percent. In actual practice the choice within such a relatively small range of parametric values would be dependent upon the airlines financial situation and their future objectives. Based upon these findings, the preferred ALR aircraft will have a payload within the range of 68.0 tonnes (75 tons) to 181.4 tonnes (200 tons). Note that the carrier ROI for the ALR shows a clear advantage over the reference fleet ROI for ALR payloads up through 362.9 tonnes (400 tons).

Specific requirements for a range of payloads when the manufacturers ROI is set at 15 percent are presented in Table 4. The number of aircraft required increases with decreasing payloads until the 68 tonne (75 tons) capacity is reached. At small payloads the competitiveness of the advanced long range aircraft decreases, with a resulting increase in the number of DMR, CLN and CW aircraft required during the 14 year period. This observation explains the 26 percent decrease in the number of ALR units in Table 4 when the payload is reduced from 68 tonne (75 tons) to 45.4 tonne (50 tons). Also shown are the aircraft prices compatible with the number of aircraft required and a manufacturers ROI of 15 percent. The airline ROI shows a continuous increase until the payload is reduced to the 68 tonne (75 tons) level at which point the operating cost of the aircraft begins to predominate and reduces the airline ROI.

A point of concern and one deserving of further analysis is the impact of trip frequency in selecting the size of future aircraft. Table 4 shows the average annual growth in the number of trips per year performed by the total fleet (ALR, DMR, CLN and CW) to meet the forecast market demand beginning in 1994. The resulting frequencies in the year 2008 represent a four-, three- and two-fold increase over the 1994 values for the 68 tonne (75 tons), 90.7 tonne (100 tons) and 181.4 tonne (200 tons) payload ALR fleets, respectively. The analysis further shows that there was already a two-fold increase in frequency going from the 1978 cargo fleet to the 1994 fleet. The CLASS airport and terminal surveys discussed previously indicate that such increase in operations could lead to serious saturation problems at many major airports in spite of the ground installation improvements projected out to the year 1990. In addition, the forecast reduction of indirect operating cost to 30 percent of the total revenue could probably not be achieved under such conditions. While these congestion problems suggest the need for reduced frequencies afforded by larger aircraft, conventional configurations of aircraft for payloads much in excess of 149.7 tonnes (165 tons) will encounter airport

oriented problems due to their length, span, gear tread, and noise.

The resulting fleet mixes for the various sizes of ALR aircraft are shown in figure 11. Note that the number of the respective ALR's have not been cumulated. For instance, the total number of DMR and ALR units required in 2005 with the 453.6 tonne (500 tons) ALR is approximately 375 and around 480 units with the 272.2 tonne (300 tons) version. This analysis shows that due to the relative improvements in efficiency of the DMR over CW, the latter fades out of the picture about the year 2002 while the derivative aircraft remains strong out to 2008. The ALR begins to dominate the market by 2005, with the number of ALR units strongly affected by the ALR design payload.

#### CONCLUDING REMARKS

This analysis of the prospects for a new, large dedicated freighter has considered the problems of integrating this vehicle into the air cargo infrastructure. Market forecast were then projected through 2008 to enable a computer simulation program to compete current, derivative and advanced freighter aircraft using return on investment to both the carrier and manufacturer as criteria. The final analysis of the simulation studies were in process when this report was being prepared, so these results must be considered preliminary. Thus, the final Douglas report on this task (CLASS-vol 4: Future Requirements of Dedicated Freighter Aircraft to Year 2008, NASA CR-158950) may shed additional light on the question of new freighter development. No consideration has been given to the impact of military purchases of an advanced design which could serve both civil and military needs. The additional production run would improve the manufacturer's ROI. Subject to these caveats, the study produced the following results:

- o The surveys of potential users suggest latent demand that could be stimulated with a dedicated, intermodal air cargo operation.
- o New freighter aircraft must compete with current wide-bodies and their derivatives.
- o Aircraft much larger than the B-747 will incur problems
  - economic: low production quantity portends low manufacturer ROI
  - system interface: airports sized by current wide-body aircraft (runway, taxiway, gate access)
  - environmental: noise scales with size
- o The hub/spoke distribution system may be one solution to the present congestion dilemma which could pave the way for new freighter aircraft.
- o Market forecast and computer simulation studies indicate 1994 demand for advanced technology, long-range freighter aircraft with design payload between 75 and 200 tons.

## REFERENCES

1. Cargo/Logistics Airlift Systems Study (CLASS). Lockheed-Georgia Company. Volume I, NASA CR-158915; Volume II, NASA CR-158916; and Executive Summary, NASA CR-158959, 1978.
2. Cargo/Logistics Airlift Systems Study (CLASS). Douglas Aircraft Company. Volume I, NASA CR-158912; and Volume III, NASA CR-158914, 1978.
3. Whitehead, Allen H., Jr.: Characteristics of Future Air Cargo Demand and Impact on Aircraft Development (A Report on the Cargo/Logistics Airlift Systems Study (CLASS) Project). NASA TM 78774, 1978.
4. Technical and Economic Assessment of Swept-Wing Span-Distributed Load Concept for Civil and Military Air Cargo Transport. NASA CR-145229, 1977.
5. Whitehead, Allen H., Jr.: Preliminary Analysis Hub and Spoke Air Freight Distribution System. NASA TM 72656, 1978.
6. Air Cargo: An Integrated Systems View. NASA CR-145384, 1978.
7. Greenfield, David: Steward Airport Builds Its Future on Cargo. Air Cargo Magazine. March 1979, pp. 6-10.

TABLE 1  
1980 TECHNOLOGY APPLIED TO DERIVATIVE TRANSPORT AIRCRAFT

TECHNOLOGY FOR DERIVATIVE AIRCRAFT	INCREMENTAL CHANGE FROM CURRENT AIRCRAFT							
	$\Delta W_{P+N}$	$\Delta L/D$	$\Delta SFC$	$\Delta W_{ENG}$	MANUFACTURING COST		MAINTENANCE COST	
	$\Delta W_{STRU}$			$\Delta W_{FURN}$	AIRCRAFT	ENGINE	AIRCRAFT	ENGINE
COMPOSITES	-8%				-1%			
IMPROVED ENGINE			-8%	-2%				
REDUCED DRAG		+4%						
ACTIVE FLIGHT CONTROLS	-2.5%							
CARBON BRAKES	-1%							
TOTAL IMPACT	-8%	+4%	-8%	-2%	-1%			
	-11.2%							

TABLE 2  
1990 TECHNOLOGY APPLIED TO NEW FREIGHTER AIRCRAFT

TECHNOLOGY FOR NEW FREIGHTER AIRCRAFT	INCREMENTAL CHANGE FROM CURRENT AIRCRAFT							
	$\Delta W_{P+N}$	$\Delta L/D$	$\Delta SFC$	$\Delta W_{ENG}$	MANUFACTURING COST		MAINTENANCE COST	
	$\Delta W_{STRU}$			$\Delta W_{FURN}$	AIRCRAFT	ENGINE	AIRCRAFT	ENGINE
COMPOSITES	-24%				-3.5%		-2%	
ADHESIVE BONDING					-10%			
NEW ENGINES			-13%	-4%		+7.2%		-5%
SUPERCritical WING		+8%						
ACTIVE FLIGHT CONTROL	-5.5%	+3%			-1%			
IMPROVED AIRCRAFT SYSTEMS				-9.5%				
CARGO LOADING SYSTEM	-4%							
CARBON BRAKES	-1%							
TOTAL IMPACT	-24%	+11%	-13%	-4%	-14%	+7.2%	-2%	-5%
	-32%			-9.5%				

TABLE 3  
DESIGN REQUIREMENTS

1995 ADVANCED LONG RANGE FREIGHTER (1994-2008)

- RANGE = 7023km (4364 STATUTE MILES)
- 1994 DOLLARS

PAYLOAD - (TONNES) (TONS)	90.7 (100)	181.4 (200)	272.2 (300)	362.9 (400)	453.6 (500)	544.3 (600)
TRIP COST - (\$)	48 210	92 198	139 755	190 841	245 468	303 647
A/C PRICE (\$ x 10 <sup>6</sup> )	61	104	143	180	215	249
NUMBER OF AIRCRAFT	937	473	313	234	190	147
AIRLINE ROI (%)	24.5	26.1	27.0	27.6	27.9	27.1
MANUFACTURER ROI (%)	17.5	4.5	-4.0	-10.0	-15.0	-18.5

TABLE 4  
DESIGN REQUIREMENTS

1995 ADVANCED LONG RANGE FREIGHTER (MANUFACTURER ROI = 15%)

- RANGE = 7023km (4364 STATUTE MILES)
- 1994 DOLLARS

PAYLOAD - (TONNES) (TONS)	45.4 (50)	68.0 (75)	90.7 (100)	181.4 (200)	272.2 (300)	453.6 (500)
NUMBER OF AIRCRAFT	922	1253	937	473	313	190
ANNUAL FREQUENCY GROWTH*	9.6	10.4	8.9	6.0	4.7	3.4
A/C PRICE - (\$ x 106)	36	42	59	133	222	430
AIRLINE ROI (%)	22.3	25.1	24.8	23.8	22.7	21.1
MANUFACTURER ROI (%)	15	15	15	15	15	15

\*REFERENCED TO A 1994 BASE FOR THE DERIVATIVE FLEET (DMR, CSN, CLN) OF 1067 FLIGHTS PER DAY

LEVEL	WHY? HOW?	WHAT?	WHO?
	DECISION CRITERIA	IMPACT	DECIDING AGENT
DIRECTION OF INCREASING SYSTEM COMPLEXITY ↓	1. SHIPPER TRANSPORTATION COST	MODE CHOICE	TRANSPORTATION AGENT
	2. SHIPPER TOTAL COST OF DISTRIBUTION	MODE CHOICE	SHIPPER MANAGEMENT
	3. AIRPLANE MANUFACTURER ROI	SIZE/QUANTITY OF AIRCRAFT	MANUFACTURER MN'GT.
	4. CARRIER SYSTEM ECONOMICS	FREQ., ROUTES, TARIFFS AND QUANTITY OF AIRCRAFT, ETC.	CARRIER MN'GT.
	5. TRANSPORTATION SYSTEM ATTRIBUTES (AIRPORT CAPACITY AND CAPABILITY; SURFACE-MODE INTERFACE; CURFEWS; DOCUMENTATION; SECURITY; ETC.)	LEVEL OF SERVICE; DOOR-TO- DOOR COSTS	AIRPORT AUTHORITIES, LOCAL GOVERNMENTS
	6. DOMESTIC REGULATORY CHANGES	MODAL SHARE SPLIT, LEVEL OF SERVICE, TARIFFS	ICC, CAB, DOT
	7. NATIONAL OBJECTIVES •TRADE EXPANSION/CONTRACTION •DIPLOMATIC RELATIONS •STRATEGIC MOBILITY	TOTAL FREIGHT MOVED  AIRCRAFT DEMAND	DOC, STATE DEPT., EXEC. BRANCH DOD, EXEC. BRANCH
	8. BILATERAL TRADE AGREEMENTS	TOTAL FREIGHT MOVED, TARIFFS, TYPES OF AIRCRAFT, LEVEL OF SERVICE	WORLD GOVERNMENTS

Fig. 1 Hierarchy of decision criteria impacting air cargo.

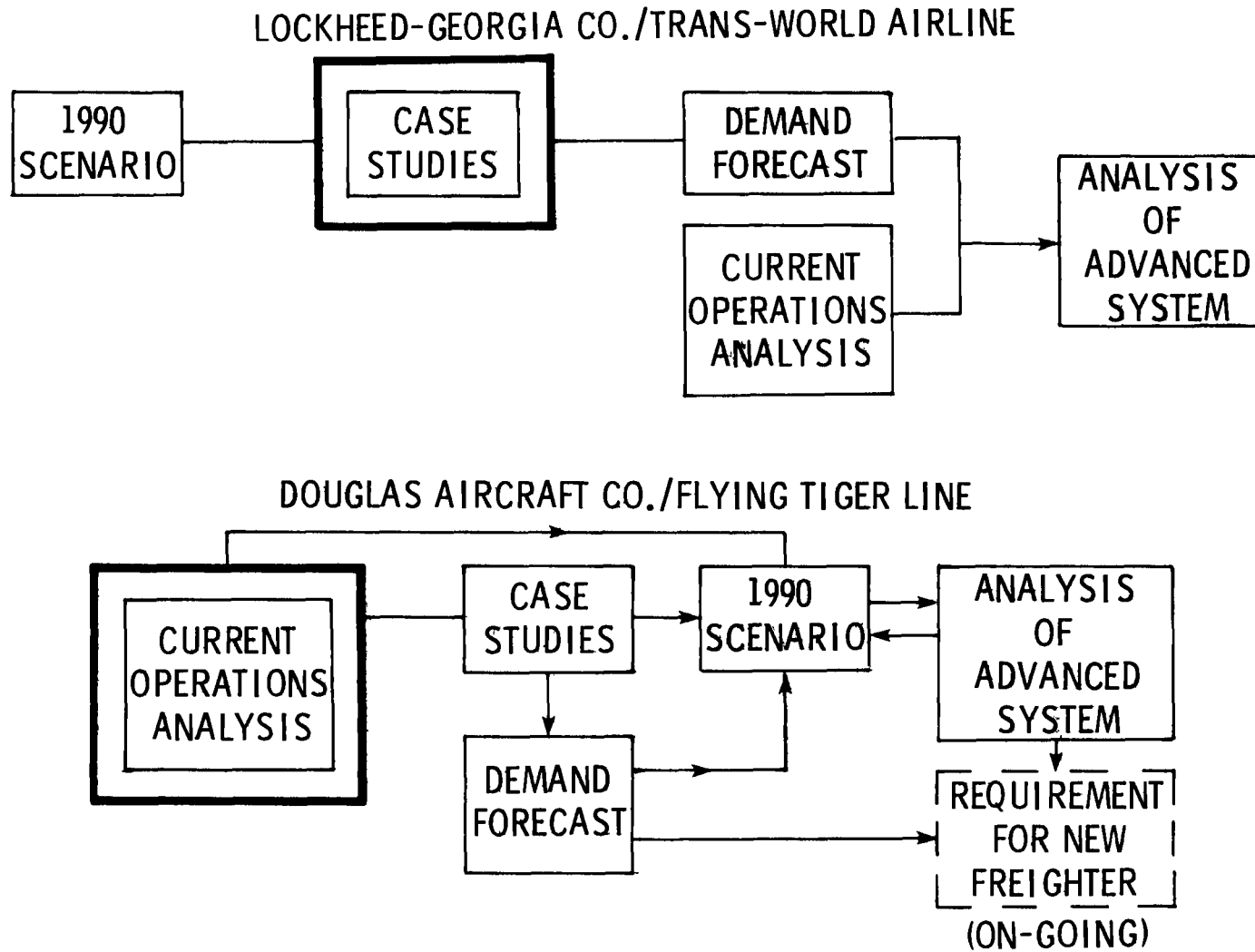


Fig. 2 Comparison of contractor methods.

IMPROVEMENTS		PERCENT REDUCTIONS			
		DOC	IOC	TOC	RATES
1978-1985	● INCREASED LOAD FACTOR (65-70 %)	7		4	4
	● SHIPPER-PACKED CONTAINERS WITH INCREASED CUBE UTILIZATION FROM 54 TO ABOUT 85 %		23	10	9
	● IMPROVED TERMINAL TECHNOLOGY		6	2	2
		15			
1985-2000	● FREIGHTER AIRCRAFT/AIRPORT COMPATIBILITY		4	1	1
	● ECONOMY OF SCALE WITH LARGE VOLUME OPERATION		15	6	6
	● ADVANCED TECHNOLOGY FREIGHTER	13-23		7-12	3-6
		10-13			
● INCREASED AIRLINE PROFIT					-4
TOTALS		20-30	48	30-35	21-24

Fig. 3 Cost reductions through system improvements.

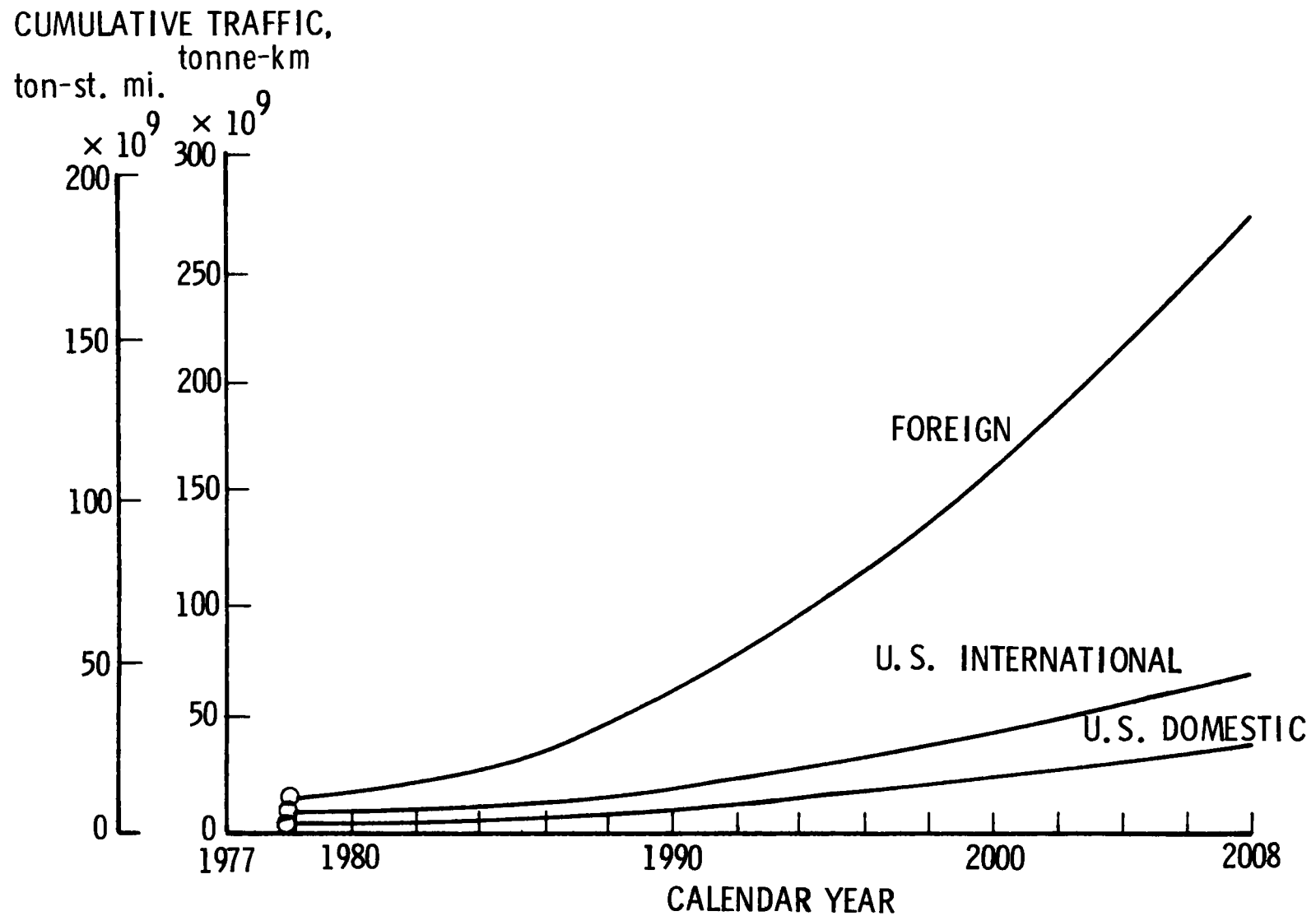


Fig. 4 Air freight market forecast for all-cargo aircraft.

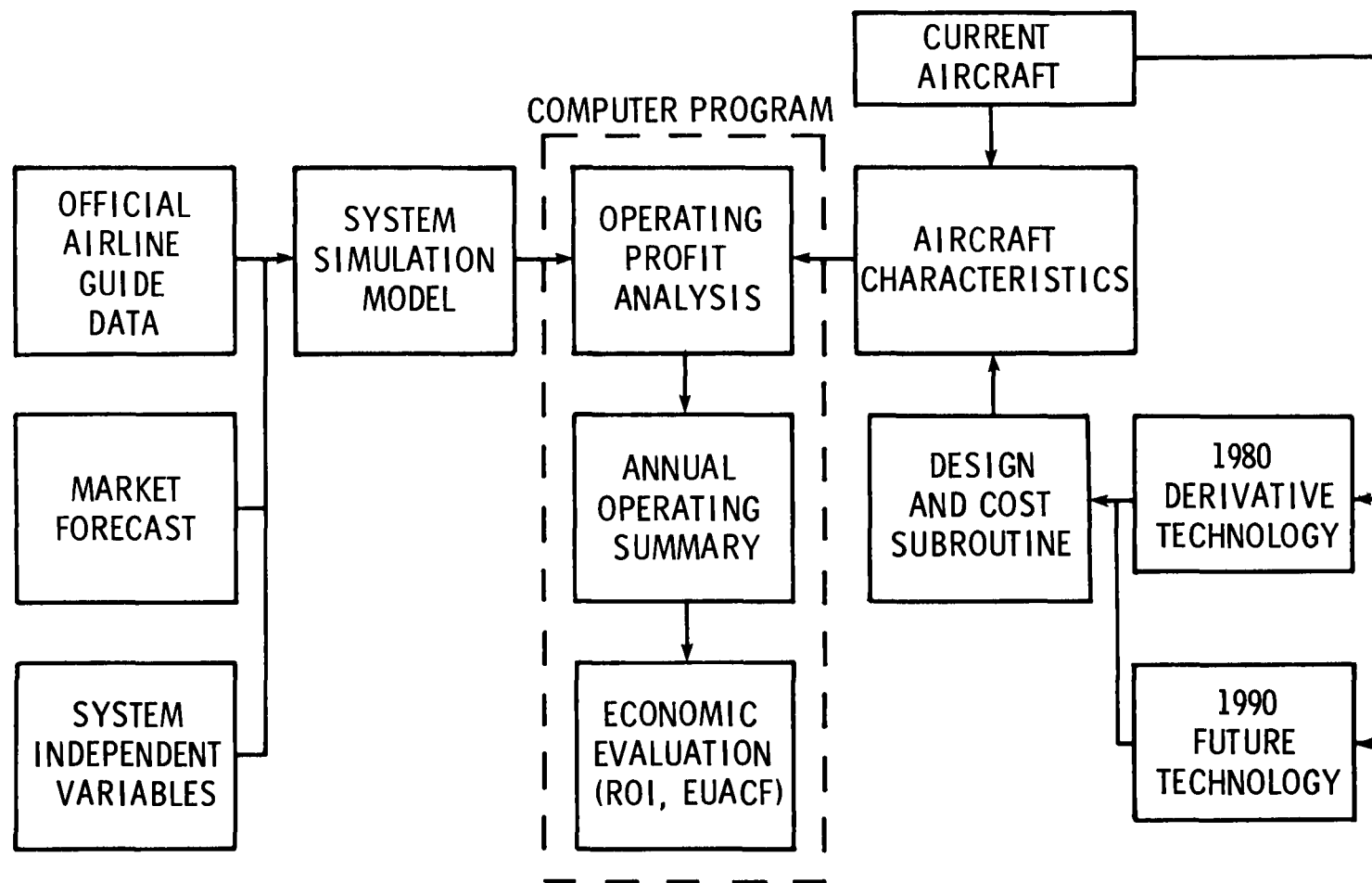


Fig. 5 Parametric analysis.

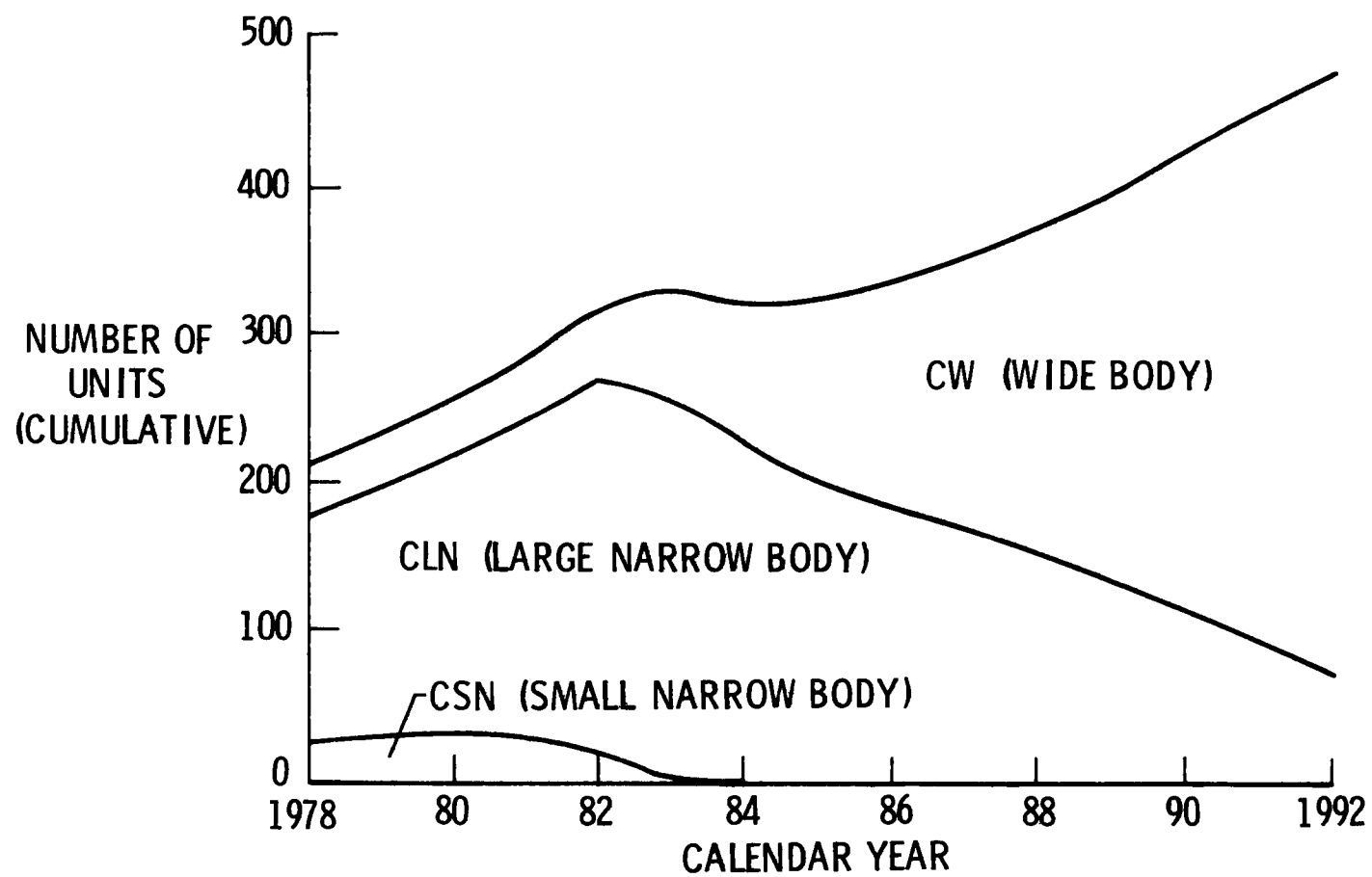


Fig. 6 Current aircraft fleet mix (1978-1984).

# 1980 TECHNOLOGY, 1984 DOLLARS

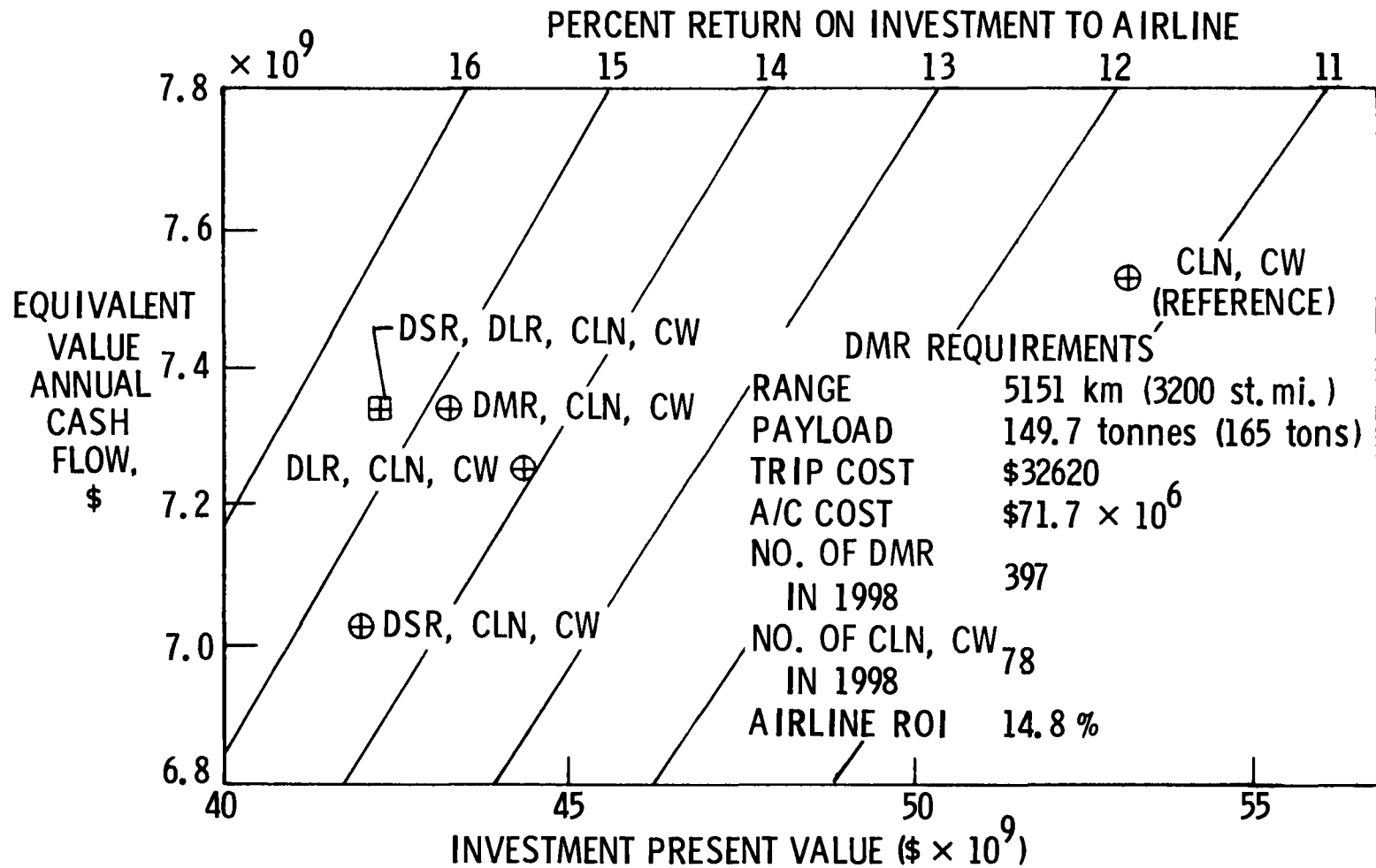


Fig. 7 Economic evaluation of derivative aircraft (1984-1998).

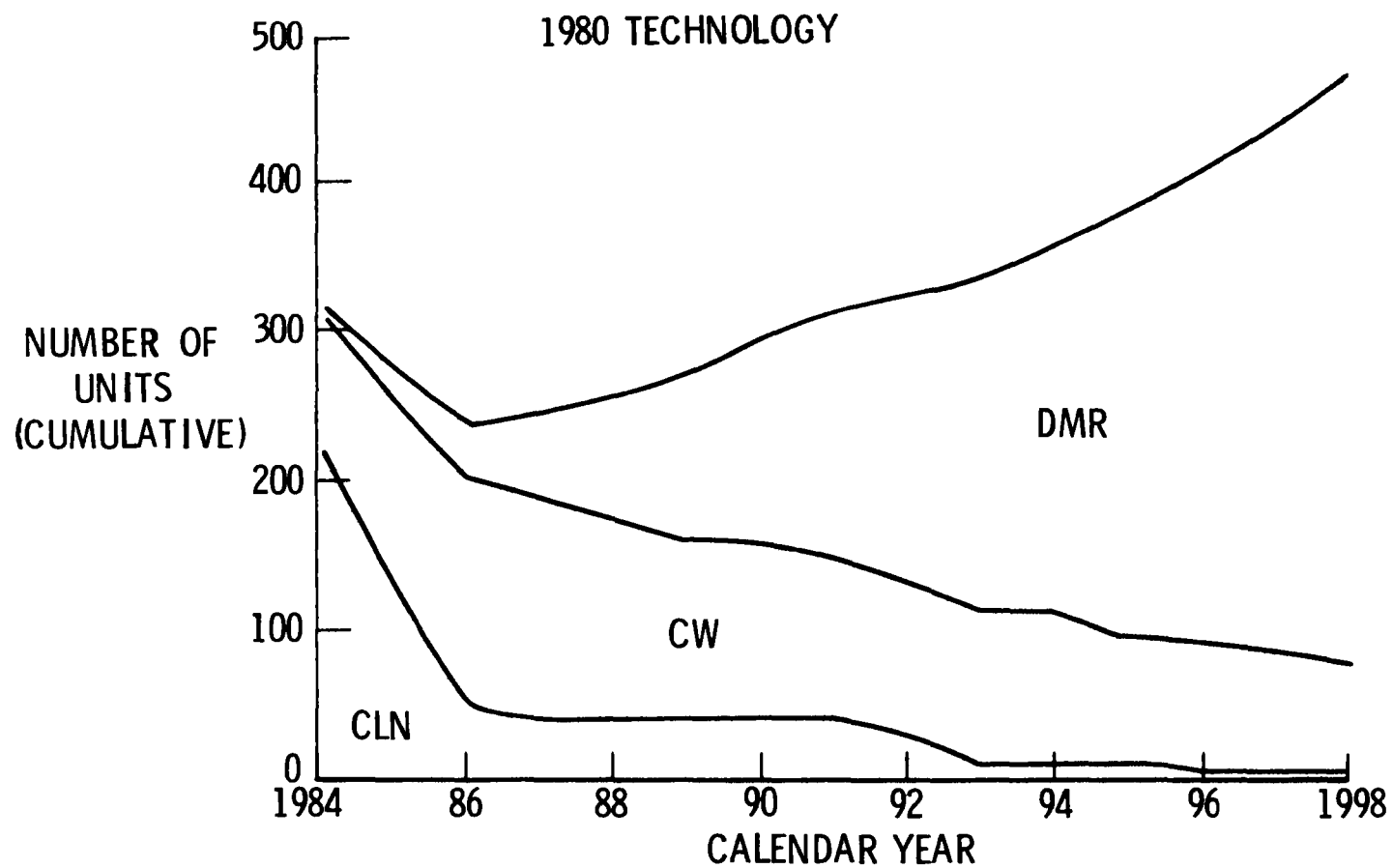


Fig. 8 Current and derivative aircraft fleet mix (1984-1998).

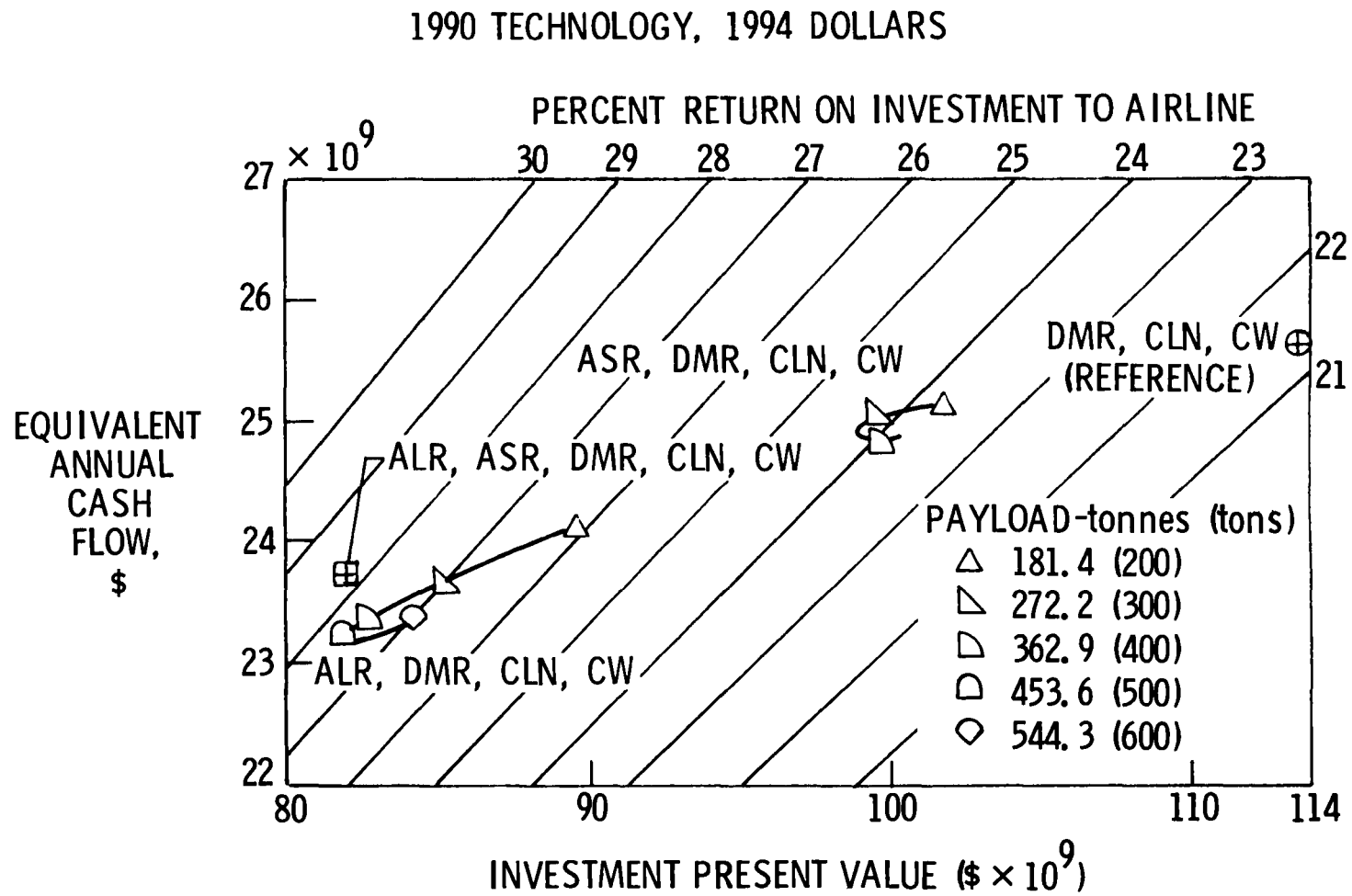


Fig. 9 Economic evaluation of advanced long range freighter (1994-2008).

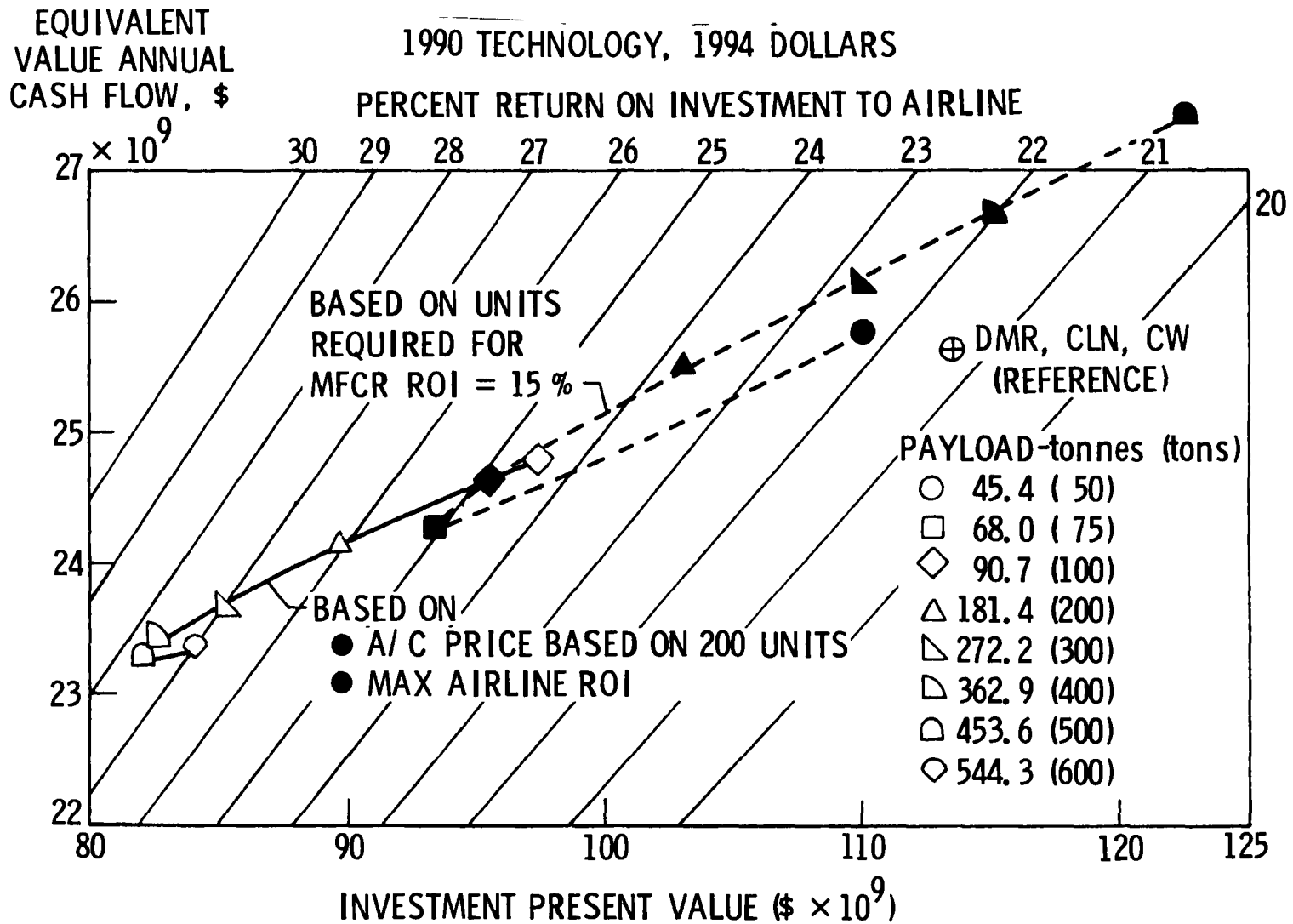


Fig. 10 Economic evaluation of advanced freighters (1994-2008).

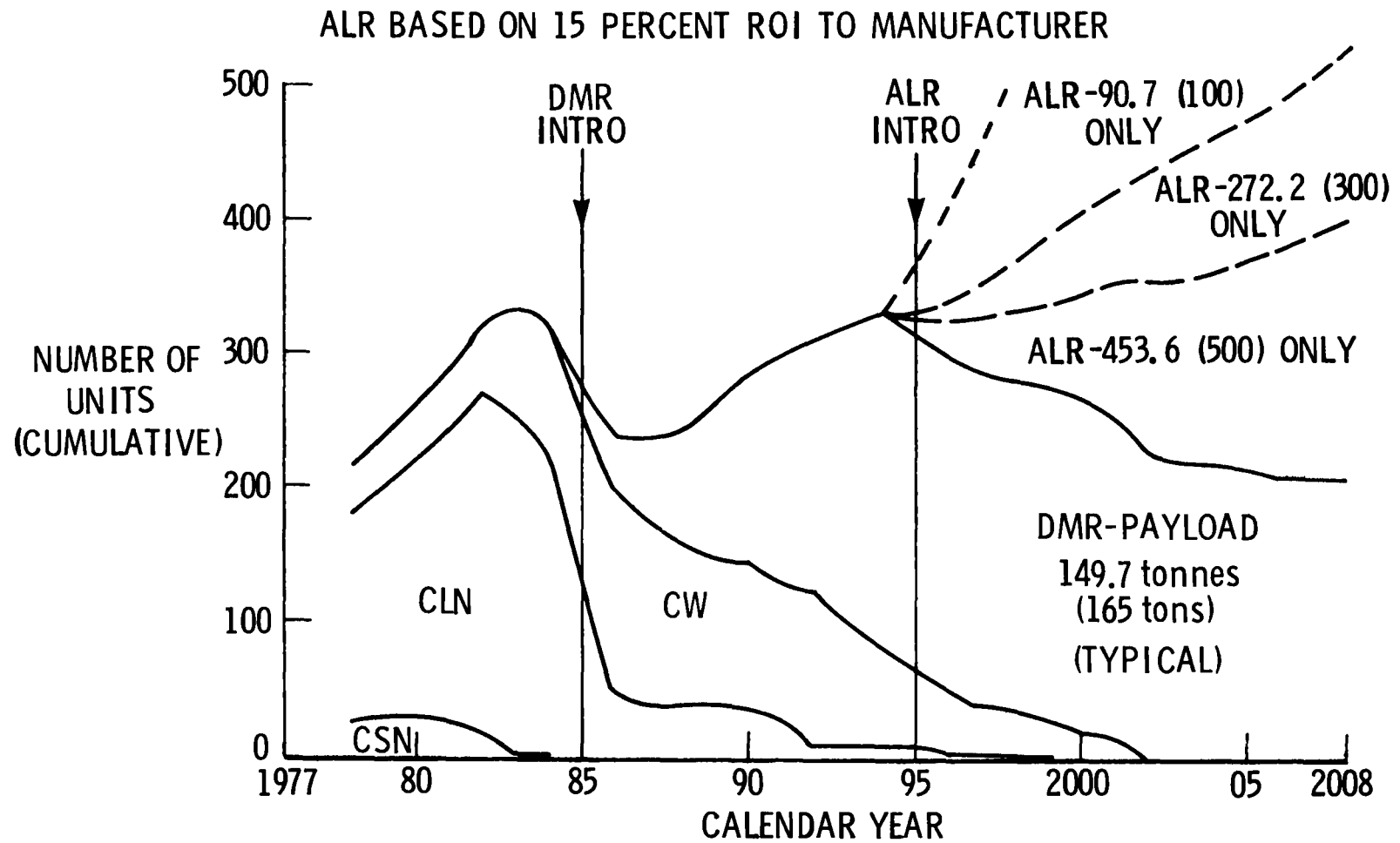


Fig. 11 Current, derivative and advanced aircraft fleet mix (1978-2008).

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